APPLICATION OF BETATRON OSCILLATION RESONANCES FOR EMITTANCE SHAPING AND BEAM LOSS LOCALIZATION IN THE UNK

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Abstract: This paper shows the possibility of using betatron oscillation resonances for shaping the beam cross section and loss localization in the UNK. This technique allows one to simplify essentially the system design and to raise the efficiency of its performance. The results on the experimental test at the 70 GeV accelerator are presented.

1. Introduction

A sharp boundary of the beam circulating in the UNK is formed with a system of emittance shaping which consists of an inner absorber, scattering target, system of collimators and bump magnets. The circulating beam is transferred to the absorber edge at the end of the working region of the vacuum chamber using the local orbit distortion. In this, the particles escaping the boundaries of the emittance required hit the target protruding into the machine aperture behind the absorber edge. The particles scattered on the target are stepsized onto the absorber.

The fluxes of secondaries emitting from the absorber are captured by the system of moving collimators. The intensity of secondary emission is decreased with an increase of the rate of stepsize onto the absorber and a decrease in the density of the absorber edge. In this paper we put forward the idea of using for this purpose nonlinear resonances of betatron oscillations.

To shape the cross section of the circulating beam, two systems of shaping the emittance are envisaged. Here we propose to use the $Q_r=Q_z$ coupling resonance to shape the beam cross section on one absorber.

2. Using Resonances to Localize Loss of Particles not Captured into the Acceleration Process. Experimental Test of the Technique at the U-70 Machine

The correction system for the UNK ensures the required value of chromaticity, $x_{r,z}=5$, for the stable operation within the whole acceleration cycle [1]. In a special operational mode, the value of chromaticity, $x_r=+50$ and $x_z=+5$, is established to capture the particles left out of acceleration. Figure 1 shows the frequency Q_r versus momentum under these operational conditions. As is seen, the particles not captured in the acceleration process, when turning into the machine chamber, will pass through the third-order resonance $3Q_r=110$ and then through the second-order one, $2Q_r=73$.

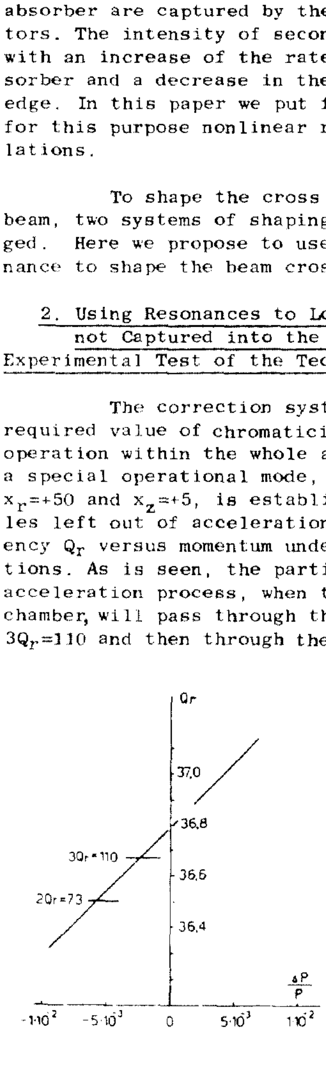

Fig.1. Q_r vs momentum for $x_r=+50$.

The beam having an emittance of $Э_{r,z}=1$ mm·mrad and momentum spread of $\Delta P/P=\pm 1\cdot 10^{-3}$ will be injected from the 1st phase, the 400 GeV conventional accelerator, into the 2nd one, the 3 TeV superconducting machine. The lost fraction of the beam, when passing through the resonance, raises the amplitude of radial oscillations. The resonance harmonic of sextupole field nonlinearity is generated by the sextupole lenses of the chromaticity correction system. Its amplitude is accepted to be

$$A_m = \frac{1}{c}\int_0^L \frac{1}{2B_oR_o}\frac{d^2S}{dr^2}\,|\varphi|_r^3\, e^{-im2\pi x/L}\,dx = 300.$$

Here C=1 m is a dimensional coefficient, B_o is the magnetic inductance, R_o is the orbit curvature radius, $|\varphi|_r$ is the Flocke function modulus, m=100 is the harmonic number, L is the machine orbit length.

This value of the amplitude of resonance harmonic ensures the 10-12 mm beam stepsize onto the absorber for particles having a small initial amplitude of betatron oscillations. The rate of amplitude variation at the beginning of acceleration should be decreased by an order of magnitude. Then when third-order resonance is passed through, the particles having an emittance of

$$Э > \frac{64c\chi_r}{|A_m|^2 P}\cdot\frac{dP}{dn} = 0.035 \text{ mm·mrad}.$$

will be captured into resonance.

The remaining (2-3)% of particles will reach the second-order resonance to be excited and stepsized onto the absorber. The chosen value for the amplitude of resonance harmonic of field gradient is such that the 12 mm stepsize should be ensured.

When the resonance is excited, the stability of the primary beam becomes a problem. The resonance width of the beam with $Э=1$ mm·mrad is $\delta_{res}=1.8\cdot 10^{-2}$. For x=+50 and $\Delta P/P=1\cdot 10^{-3}$ the beam width over frequencies is $\pm 5\cdot 10^{-2}$. Therefore the working point chosen is at a distance of 0.1 farther from the third-order resonance.

Somewhat dangerous are the forth-order resonances excited by a random spread of the octupole field nonlinearities of the dipoles. The tolerance for a relative value of the field additive caused by the octupole nonlinearity at the edge of the accelerator aperture is $B/B=2\cdot 10^{-4}$ [2], in which case the value of the resonance detuning up to the line $4Q_r=147$ is only $\sigma_{res}=1.2\cdot 10^{-4}$. The distance $\Delta Q=0.001$ up to the resonance makes a good provision for the primary beam stability. In addition, the correction system for the octupole nonlinearity allows one to suppress this resonance. The stability of the primary beam was simulated for its multipole crossing caused synchrotron oscillations of the lines of the unsuppressed resonances. In this case there was a 20% increase of the initial beam emittance.

The tolerance for a random spread of the decapole nonlinearity is $\Delta B/B=5\cdot 10^{4}$. Simulation of multiple crossing the lines of the fifth-order resonance increases the emittance by 20%.

The technique was tested experimentally at the U-70 IHEP accelerator when the beam was recaptured from the accelerating frequency 60 MHz for 200 MHz at the cycle flattop at 70 GeV. In order to raise the measurement accuracy, the value of the intensity not captured into the separatrix was chosen to be ~40%. The resonance of radial betatron oscillations, $3Q_r=29$, was excited by two pairs of sextupole lenses of the slow extraction system. The acceleration process was simulated by varying the main field of the machine. In this case, the particles captured into the separatrix 200MHz were accelerated again and those left out of acceleration were stepsized onto the inner absorber.

Figure 2 shows the distribution of the protons stepsized onto the absorber in the case of localizing particle loss with the betatron oscillation resonance on (b) and off (a).

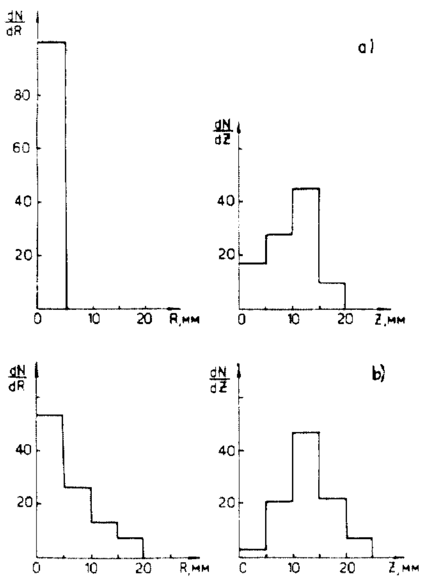

Fig. 2. Distribution of particles at the absorber input: a) target stepsize onto the absorber; b) resonance and scattering target stepsize onto the absorber.

To estimate the effect of the resonance on the beam accelerated, its dimensions were measured after recapture with the help of a fast scanning device consisting of two thin wires fixed to the common holder. Therefore the signal from the monitor has the shape of two distributions. The oscillograph shows fairly well the shift in the position of the beam not captured into the acceleration process with respect to the primary one. The measurement results presented in fig.3 show that with the betatron oscillation resonance used for loss localization, this does not lead to a noticeable increase in the cross section of the primary beam.

3. Application of Coupling Resonance for Shaping the Transverse Beam Emittance

With a growth of the amplitude of vertical betatron oscillations due to any reasons, a simultaneous increase in the amplitude of radial oscillations is observed in the $Q_r=Q_z$ resonance. This circumstance can be taken advantage of for scraping on one absorber the beam halo in two planes.

During radial scraping of the beam up to the amplitude A_r under the conditions of the coupling resonance, the vertical amplitude is scraped to take the value

$$A_z = A_r \cdot \frac{|\varphi|_z}{|\varphi|_r} \, \frac{\omega + \pi\delta}{p} ,$$

where $|\varphi|_{r,z}$ is the Flocke function modulus,

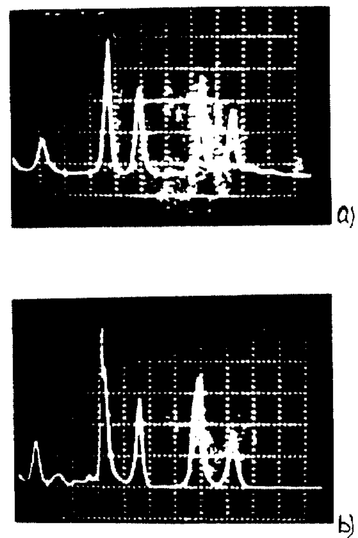

Fig. 3. Radial distribution of the primary circulating beam: a) loss localization without the betatron oscillation used; b) less localization with the resonance used.

$$\omega = \sqrt{p^2 + \pi^2\delta^2}, \quad p = \int_0^L \frac{G}{cB_0B_0} \cdot |\varphi|_r |\varphi|_z dx$$

and $\delta = |Q_r - Q_z|$. In this case, the amplitudes of different directions exchange with the following period:

$$T = (\pi/\omega) \text{ turns}.$$

To produce the coupling resonance in the UNK one may use skew quadrupole lenses of the correction system. The particles are stepsized onto the absorber with the help of a 0.2 mm thick tungsten scattering target protruding 2 mm after the absorber edge. The absorber is placed in Matched Straight Section (MSS) 1. Two collimators confining the machine aperture up to Ø 70 mm are placed at a distance of 50 m after the absorber in front of the 1st quadrupole lens downstream.

In numeric calculations, beam scattering was simulated for different time constants in the vertical plane in the residual gas. The resonance width was chosen to be p=0.064 and the ratio of the amplitudes of betatron oscillations after scraping on the radial absorber up to the amplitude A_r for detuning δ =0.01 was

$$A_z/A_r = 1/17 \, |\varphi|_z / |\varphi|_r .$$

The initial beam contained 2000 particles having a normal momentum distribution with a RMS deviation of $\sigma_{\Delta p} = \pm 2 \cdot 10^{-3}$ and the Rayleigh distribution over the amplitudes of horizontal and vertical betatron oscillations.

The results on the numeric simulation of beam scraping up to an emittance of 0.8 mm·mrad at 70 GeV are given in Table. The 1st column shows the increase of the beam halfsize for the case when no scraping was done. The histograms of the distribution of the beam density on the absorber are shown in fig.4.

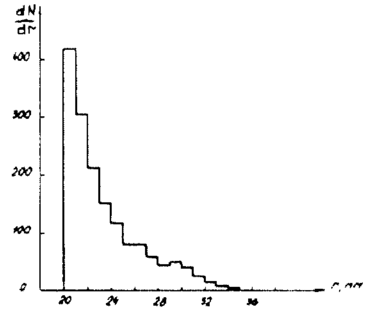

Fig. 4. Histogram of the beam density distribution on the absorber.

Scraping is carried out without an increase in the vertical beam dimension provided the vertical smear does not exceed the rate of oscillation energy exchange due to the coupling resonance. The Table shows that this occurs for such blow-up rates when the beam dimensions are doubled due to destabilizing factors within 1000 turns or 70 ms. With so fast processes, the system of emergency beam dump onto the outer absorber must evidently be turned on.

Table

Variation in the vertical beam half-size within 1000 turns, $\|\varphi\| = 20$ m	Particle losses walue			$\frac{A_z \|\varphi\|_r}{A_r \|\varphi\|_z}$
	on absorber	on collimators	on the machine chamber	
mm	%	%	%	
3	88	5	7	1.06
8	88	9	3	1.11
16	90	6	4	1.22
26	93	5	2	1.33
38	93	5	2	1.44

During scraping the beam halo when it passes through the scattering target, a noticeable increase of the amplitude of radial betatron oscillations and loss of the momentum of the circulating particles take place. This may enhance the effect of the neighbouring resonances and influence the distribution of beam loss along the machine chamber. In addition, detuning the frequencies of the main oscillations during the coupling resonance excitation causes the working point to shift to the third-order resonance $3Q_r=110$ with a random spread of the sextupole nonlinearities of the dipoles.

Figure 5 shows the working square of frequencies. Near the working point there are the nodes of the lines of the third-, tenth-, seventh-, eleventh-, fourth-order resonances, the lines of the resonance $Q_r=Q_z$ and $2Q_r=2Q_z$. The lines of the higher-order coupling resonances are not shown as they would have obscured the figure.

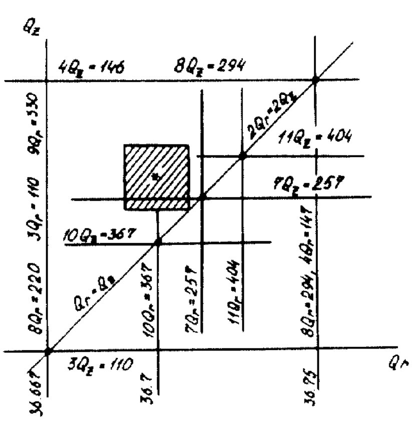

Fig. 5. Beam working region on the frequency square during beam scraping.

The effect of the coupling resonance $2Q_r=2Q_z$ is an inessential increase of the value of the stepsize onto the absorber. The distribution of the particle loss along the ring is actually unchanged. With a growth in the amplitude of radial betatron oscillations during scraping the effect of the resonance $3Q_r=110$ is a 25% increase in the value of the stepsize onto the absorber. In this case the loss distribution does not vary. The seventh-order resonances at a random spread of the dipole nonlinearities do not affect the emittance shaping process. The effect of the tenth- and eleventh-order resonances was not taken into account.

The experimental test of the technique carried out at the U-70 IHEP accelerator showed a good agreement with the calculation. For the resonance width $p=0.008\cdot\pi$ produced by the correction system and the detuning $\delta = 1\cdot 10^{-3}$ the ratio between the amplitudes of betatron oscillations after vertical beam scraping was

$$\frac{A_r}{A_z} = 1.23 \frac{|\varphi|_r}{|\varphi|_z},$$

while the calculated value was

$$\frac{A_r}{A_z} = 1.12 \frac{|\varphi|_r}{|\varphi|_z}.$$

4. Conclusions

Application of betatron oscillation resonances allows one to simplify essentially the system design and raise the efficiency of emittance shaping and of particle loss localization in the UNK. In addition, the primary beam remains stable.

References

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[3] V.I.Balbekov, P.I.Chirkov. Preprint IHEP 81-23, Serpukhov, 1981.